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Galaxy Dynamics from Edge-On Late-type Galaxies

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Abstract. We present first results of a program to study the dynamics of undisturbed bulgeless, low surface density disk galaxies in order to probe the underlying structure of dark matter halos. High resolution H α rotation curves are combined with optical and infrared imaging to place strong limits on the halo profiles. We find noticeable variation in the shapes of the rotation curves, in contrast to previous claims. The implied density profiles are still significantly more shallow than profiles derived from most N-body simulations; unlike previous HI observations, beam-smearing cannot significantly affect this result. Based upon stellar mass profiles derived from K' band observations, we derive the angular momentum distribution of the stellar disk and find it to be broader than that of a uniformly rotating solid-body sphere, but remarkably consistent from galaxy-to-galaxy. Finally, based upon K' band surface brightness profiles, we find that low surface density disks must be significantly submaximal. Furthermore, maximal disk fits based upon Modified Newtonian Dynamics (MOND) have maximum mass-to-light ratios which are too small to be consistent with stellar population models; without the ability to significantly adjust inclination angles or infrared mass-to-light ratios, this sample presents great difficulties for MOND.

Although the internal structure of dark matter halos is an extremely important test of cosmological theories, few secure observational constraints currently exist. In disk galaxies, the structure of the halo is best explored with rotation curves. However, both the luminous and dark matter contribute significantly to the enclosed mass, disguising the dynamics of the dark matter halo, and altering its structure as well. Therefore, while rotation curves are the most sensitive dynamical indicators of a galaxy's total mass distribution, they are a poor measure of the dark matter profile alone.

More direct probes of the dark matter are provided by low surface brightness galaxies (LSBs). There is strong dynamical evidence that LSBs have low baryonic surface density, and thus the disk contributes little to the dynamics of the galaxy, and the resulting rotation curve is dominated by the dark halo; the few LSB rotation curves published to date rise remarkably slowly, becoming asymptotically flat only at several disk scale lengths (Goad & Roberts 1981, de Blok et al. 1996, Makarov et al. 1997, van Zee et al. 1997, van der Hulst et al. 1993). Furthermore, LSBs span a wide range in mass, and thus can be used to trace systematic variations in the shapes of dark matter halos as a function of mass.

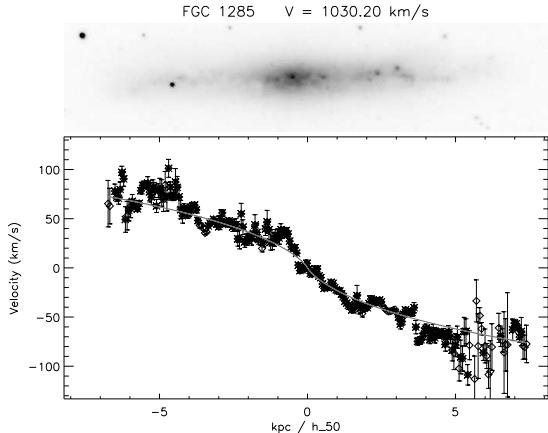


Figure 1. *R* band image (top) and extracted rotation curve (bottom), for a galaxy from the sample. All plots have been scaled to the same horizontal scale. Open symbols represent points of substantially lower signal-to-noise. In this preliminary work, rotation speed is currently extracted as the center of the $H\alpha$ line, not at the extrema as would be proper for edge-on galaxies. However, as the line widths are ± 3 km/s of the instrumental line widths, we expect little change when the proper rotation curves are extracted. Furthermore, for slowly rising rotation curves, our simulations have shown that using line centers as a measure of the rotation curve changes the rotation curve by less than 5%.

We have been pursuing a study of LSB dynamics using galaxies selected from the Flat Galaxy Catalog (Karachentsev et al. 1993), a large sample of edge-on galaxies ($a/b \geq 7$, $a > 0.6'$). We have selected 50 galaxies which appear to have low surface brightnesses when seen edge-on; because these galaxies are optically thin, their face-on central surface brightnesses will be even lower. We also required the galaxies to be completely bulgeless and undisturbed (i.e. no warps or gross asymmetries).

We obtained high resolution ($\sim 1 - 1.5''$) $H\alpha$ rotation curves for a subset of 35 of these galaxies. The rotation curves accurately probe the dynamics of the galaxies to very small radii, and at high resolution (0.1-0.5 kpc for the majority of our sample). An example image and rotation curve is shown in Figure 1. We have imaged the sample in B , R , and K' , and confirmed that all have extremely low surface brightnesses, in spite of having maximum rotation speeds up to 250 km/s; the median K -band surface brightnesses of our sample is more than 2 magnitudes per square arcsecond fainter than the median of the de Jong (1995) sample of face on spirals. The majority of these galaxies are extremely blue ($R - K < 2.5$), lack dust lanes, and lie on the B -band Tully-Fisher relationship for low luminosity galaxies of Stil (1999), all of which suggests that extinction is not a significant problem for the majority of the sample. Roughly 8 galaxies which have $R - K > 2.5$ have been eliminated from further analysis, to alleviate any concerns about extinction affecting the rotation curves.

The addition of infrared imaging to our sample allows us to accurately subtract the mass of the stellar disk (M_*) from our measured rotation curves, given the insensitivity of the K -band mass-to-light ratio to variations in star-formation history. We note, however, that HI is the largest baryonic contribution to the observed rotation curve; we find $M_{HI}/M_* \sim 1 - 4$ for our sample. The rotation curves are indeed dark matter dominated ($\langle M_{dark}/M_{baryonic} \rangle \sim 3.5$ at the last measured point).

There has been considerable attention paid in the literature to the apparent contradiction between N-body predictions of steeply rising rotation curves (cf. Navarro et al. 1997, Moore 1999; but see Kravstov et al. 1998) and HI observations of slowly rising rotation curves for dwarf and LSB galaxies (cf. de Blok et al. 1997). While there seem to be significant conflicts for dwarf galaxies, the

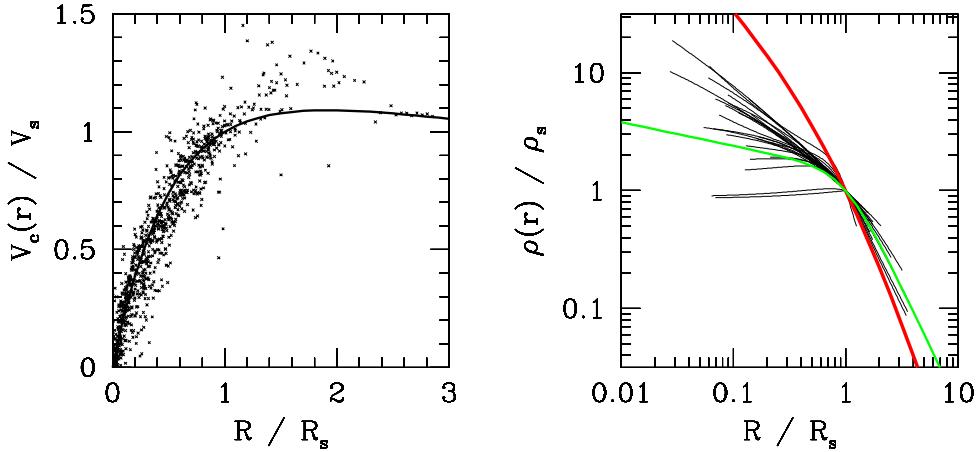


Figure 2. All extracted rotation curves are shown in the left panel, scaled by fits to the model suggested by Kravstov et al. (1998). The heavy line is the “universal” rotation curve found by Kravstov et al. Considerably more scatter is found in the high-resolution data than in the HI data plotted by Kravstov et al. – 90% of the data points fall within $\pm 20\%$ of their preferred fit. Some of this scatter is due to the low extinction of the galaxies, however (see Figure 1). The implied density profiles are plotted in the right panel. The heaviest solid line is the NFW profile, and the second heaviest line is the shallower fit of Kravstov et al. No baryonic component has been subtracted from these plots, and hence the central density profile will become shallower. No galaxies with $R - K > 2.5$ have been included, to avoid problems with extinction; 60% of the galaxies remaining have $R - K < 2.0$. Note also that the scaling by V_s and R_s in the left-hand figure masks the large variation in halo density and inner profile shape implied by the density profiles in the right-hand figure.

existing data on LSB galaxies was based upon relatively low resolution HI synthesis observations, and derived dark matter core radii which were comparable to the resolution of the beam. Kravstov et al. (1998) have used the same data to argue that all LSBs have similar rotation curves and a self-similar halo profile. In the left panel of Figure 2 we plot the comparable data for our sample of high-resolution H α rotation curves. Note that there is considerable scatter ($\pm 20\%$). The scatter also masks significant variations in the shape of the rotation curves, as can be seen by the density profiles derived from the RCs in Figure 2. Note also that the discrepancy between LSB observations and the steep cusps predicted by simulations persists at high-resolution, but that the central rotation curves are somewhat steeper than the fits of Kravstov et al. (1998).

One common feature of models of disk galaxy formation (see Mo, this volume) is the assumption of detailed angular momentum conservation for the collapse of a sphere of gas in solid body rotation (Crampin & Hoyle 1967). We test this assumption in the left panel of Figure 3, where we plot the angular momentum distributions of the stellar disk, derived from the K' observations and the rotation curve. The distributions are remarkably similar, although the data spans a factor of nearly 5 in rotation speed. The distributions are also broader than a sharp-edged sphere, as would be expected for smoother initial overdensity. Once the distribution of HI is known, we can calculate the full baryonic angular momentum distribution.

Finally, we can use the robustness of K' mass-to-light ratios ($\Upsilon_{K'}$) to measure the mass contribution which baryonic disks make to the overall dynamics.

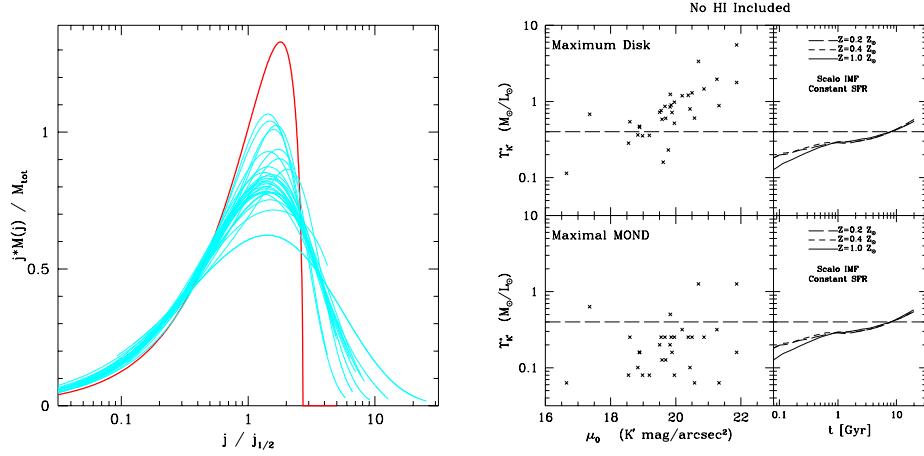


Figure 3. [LEFT] Specific angular momentum distributions, based upon exponential disk fits to the K' images and the fitted rotation curves. All curves have been scaled to $j_{1/2}$, the specific angular momentum containing half the mass, and to the same total disk mass. The heavy curve is the distribution expected for a sphere in solid body rotation, as is often assumed in disk formation models. HI has not been included. [RIGHT] Maximal Mass-to-Light ratios in K' for the stellar disk under Newtonian gravity (upper) and MOND (lower). The right panels show expected M/L for a Scalo IMF and constant star-formation, for different metallicities (Bruzual & Charlot 1999). Under Newtonian gravity, disks become systematically sub-maximal with decreasing surface brightness; the maximal disk value of $\Upsilon_{K'}$ is too high to be consistent with stellar populations. Under MOND, the stellar mass-to-light ratios are too small to be consistent with stellar population models. Including HI will make these limits more stringent.

In the right panel of Figure 4, we show $\Upsilon_{K'}$ derived from maximum disk fits to the rotation curve. The upper panel shows that disks become progressively “sub-maximal” at decreasing mass surface density. We have repeated this exercise for MOND dynamics, and find that the derived values of $\Upsilon_{K'}$ are too low to be consistent with reasonable star formation histories and normal IMFs. The contribution from HI has not been included in these fits, and will further reduce the allowed values of $\Upsilon_{K'}$, making the limits for MOND more stringent.

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